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Photonic Logic Gate Design Based on Frequency-Sensitive Optical Response of an EIT Photonic Crystal

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Abstract. The frequency-sensitive optical response due to two-photon resonance of electromagnetically induced transparency (EIT) in a tunable band structure of an EIT-based layered medium is considered. The unit cells of this periodic layered structure are composed of dielectric (e.g., GaAs) and EIT atomic vapor. The frequency-sensitive behavior of controllable reflectance and transmittance depending on the external control field can be applicable to new device design (e.g., it can serve as the fundamental working mechanism for photonic switches and photonic logic gates). Some two-input logic gates (e.g., OR and NAND gates) are designed based on the present effect of sensitive switching control that results from the two-photon resonance.

Introduction

Over the past three decades, artificial electromagnetic materials that can exhibit peculiar optical properties have attracted considerable attention in various scientific and technological areas [1]. A number of recent theoretical and experimental works have demonstrated that the effects of phase coherence control in multilevel atomic systems and semiconductor quantum dots can lead to novel quantum optical phenomena of nearly resonant light, including atomic coherent population trapping (CPT), laser without inversion (LWI), electromagnetically induced transparency (EIT) and some new applications relevant to EIT [2]. EIT that is one of the most important quantum coherent effects arises from quantum interference in energy level transitions from ground states to excited ones. It is such a quantum optical phenomenon that if only one resonant laser beam propagates through a medium, it will be absorbed; but if there are two resonant laser beams propagating in the same medium, neither would be absorbed, and hence the opaque medium would become a transparent one. Since it can exhibit many intriguing optical properties and effects [3-5], EIT could be applied to a variety of areas of optics, and enable us to achieve novel results (e.g., new unusual physical effects associated with EIT include ultraslow light pulse propagation, superluminal light propagation, light storage in atomic vapors [6-10]), some of which are expected to be beneficial (and powerful) for developing new technologies in quantum optics and photonics. Here, we will propose a possible way to manipulate light propagation with an artificial electromagnetic material based on the combination of quantum coherence and photonic crystals. Such an artificial electromagnetic material is an EIT-based periodic layered medium, which can exhibit a tunable band structure and shows extraordinary sensitivity to the

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frequency of the probe field. For example, a probe frequency change at one part in 10^8 level would lead to drastic change in the reflectance and transmittance, and therefore it might be used for designing sensitive optical switches, photonic logic gates as well as tunable photonic transistors.

A three-level atomic system and EIT-based layered structure

Consider a Lambda-type three-level atomic system with two lower levels $|1\rangle, |2\rangle$ and one upper level $|3\rangle$ (see Fig.1). This atomic system interacts with the electric fields of probe and control light waves, which drive the $|1\rangle$-$|3\rangle$ and $|2\rangle$-$|3\rangle$ transitions, respectively. Note that the parity of level $|3\rangle$ is opposite to levels $|1\rangle$ and $|2\rangle$ (since the level pairs $|1\rangle$-$|3\rangle$ and $|2\rangle$-$|3\rangle$ can be coupled to the electric fields of the probe and control lights, respectively). Such a three-level system can be found in metallic alkali atoms (e.g. Na, K, Rb). As is well known, the frequency-sensitive two-photon resonance ($\Delta_p = \Delta_c$) can be exhibited in the bulk EIT [2]. The atomic microscopic electric polarizability of the $|1\rangle$-$|3\rangle$ transition is of the form

$$\beta = \frac{\mathrm{i}\,|\wp_{13}|^2}{\varepsilon_0 \hbar} \frac{\frac{\gamma_2}{2} + \mathrm{i}\left(\Delta_p - \Delta_c\right)}{\left(\frac{\Gamma_3}{2} + \mathrm{i}\,\Delta_p\right)\left[\frac{\gamma_2}{2} + \mathrm{i}\left(\Delta_p - \Delta_c\right)\right] + \frac{1}{4}\Omega_c^* \Omega_c}. \qquad (1)$$

By using the Clausius-Mossotti relations (governing the local field effect due to the dipole-dipole interaction between neighboring atoms), the relative electric permittivity of the EIT vapor at probe frequency takes the form $\varepsilon_r = 1 + N_a\beta/(1 - N_a\beta/3)$, where Δ_p and Δ_c denote the frequency detunings of the probe and control fields, respectively, and Ω_c represents the Rabi frequency of the control field. Γ_3 and γ_2 stand for the spontaneous emission decay rate and the collisional dephasing rate, and N_a is the atomic concentration (atomic number density per unit volume) of the atomic vapor medium.

We will consider how the two-photon quantum coherence works in the composite structure of EIT and layered medium. The 1D infinite periodic (D-E) cells shown in Fig. 2 consist of two electromagnetic media [11]: GaAs dielectric (denoted by D) with the relative refractive index $n_1 = 3.54$ and a Lambda-configuration three-level EIT medium (denoted by E). We suppose that the two materials are both homogeneous along y-direction (i.e., $\partial/\partial y = 0$) and the probe signal wave propagates inside the (…D-E-D-E…) structure along x-direction, while the control field is applied to the EIT in z-axis.

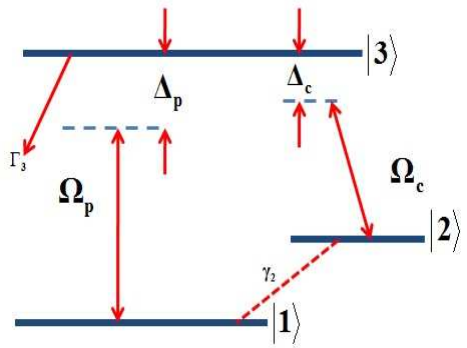

Fig. 1. The schematic diagram of a three-level EIT atomic system. The parity of upper level $|3\rangle$ is opposite to that of lower levels $|1\rangle$ and $|2\rangle$. The control and probe laser beams drive the $|2\rangle$-$|3\rangle$ and $|1\rangle$-$|3\rangle$ transitions, respectively.

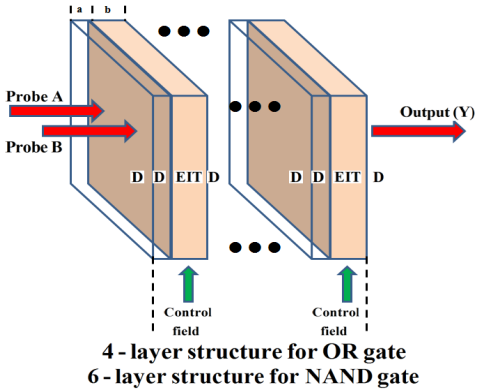

Fig. 2. The schematic diagram of an EIT-based periodic layered medium. The TE wave of the probe beam is normally incident on the left side interface ($x = 0$) of the layered medium.

Frequency-sensitive reflectance and transmittance and photonic logic gate design

The sensitive optical response found here can be utilized for designing quantum optical and photonic devices that take advantage of the effect of optical switching control. For this purpose, we need to treat the problem of reflection and transmission of the probe wave in the present EIT-based photonic crystal. The typical atomic and optical parameters chosen for Fig. 3 are as follows: the atomic number density $N_a = 5.0\times10^{20}$ m^{-3}, the electrical dipole moment $|\wp_{31}| = 1.0\times10^{-29}$ C·m, the frequency detuning of the control field $\Delta_c = 1.0\times10^{7}$ s^{-1}, the spontaneous emission decay rate $\Gamma_3 = 2.0\times10^{7}$ s^{-1} and the dephasing rate $\gamma_2 = 1.0\times10^{5}$ s^{-1}. The dramatic reduction and enhancement in the reflectance and transmittance close to $\Delta_p = 0.5\Gamma_3$ is of special interest since the two-photon resonance ($\Delta_p = \Delta_c$) can give rise to the effect of sensitive optical switching control, which would lead to promising applications to new photonic device design.

We shall briefly suggest the working mechanism of two photonic logic gates (e.g., OR and NAND gates), which can be fabricated based on such an EIT-based periodic structure. The fine structure of the reflectance and transmittance for showing extraordinary sensitivity to the frequency of the probe field is demonstrated in Fig. 3. Here we plot only the reflectance and transmittance of two cases (total number of layers $N = 4$ and $N = 6$) as an illustrative example. It can be seen that some oscillations in the curves are exhibited in the narrow resonant frequency range $\Delta_p \in [0.2\Gamma_3, 0.7\Gamma_3]$.

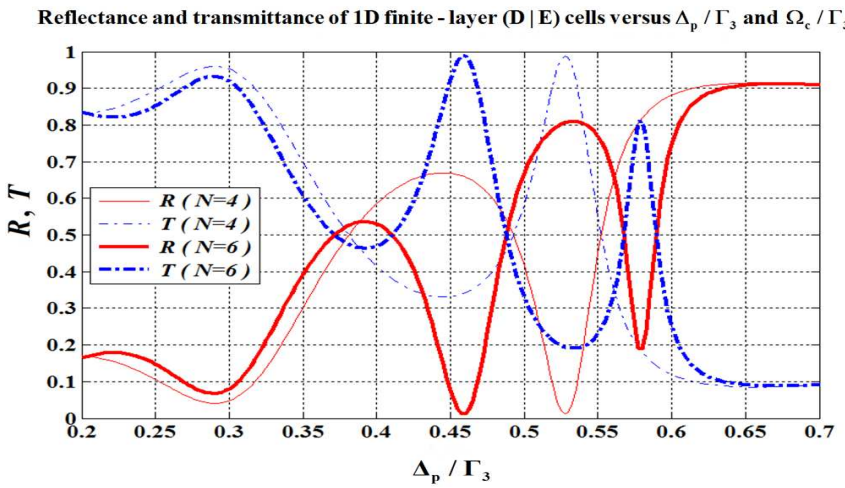

Fig. 3. The reflectance and transmittance of the 4 -layer and 6 -layer periodic (D|E) cells in a narrow probe frequency band. Here, the Rabi frequency of the control field is chosen as $\Omega_c = 2\Gamma_3 = 4.0\times10^{7}$ s^{-1}.

It can be seen from Fig. 3 that there is a local minimum (i.e., 0.19) and a local maximum (i.e., 0.99) in the transmittance T at $\Delta_p = 0.53\Gamma_3$ and $0.46\Gamma_3$, respectively, for the 6-layer periodic structure. For the 4-layer periodic structure, however, the transmittance T has a local maximum (i.e., 0.99) and a local minimum (i.e., 0.34) close to $\Delta_p = 0.53\Gamma_3$ and $0.46\Gamma_3$, respectively. Two structures with layer number $N = 4$ and 6 have been sketched in Fig. 2. Two probe beams with $\Delta_p = 0.46\Gamma_3$ and $0.53\Gamma_3$, which can act as the two input signals, are applied. We suppose that the output signal $Y = 0$ if neither of the two incident probe beams propagates through the periodic layered medium (i.e., the reflection dominates in the wave propagation of the probe field), and the output signal $Y = 1$ if at least one of the probe beams can be transmitted through the structure (i.e., the reflection and absorption can be ignored). Let the probe beams of $\Delta_p = 0.46\Gamma_3$ and $0.53\Gamma_3$ represent the input signals 0 and 1, respectively. Then the logic operations of two-input OR gate and NAND gate can be implemented with the 4-layer and 6-layer structures, respectively.

In the above, we have addressed the dispersive behavior in the case of $\Omega_c = 2\Gamma_3 = 4.0\times10^7\ \mathrm{s}^{-1}$. Note that the photonic logic gates designed in this paper can be tunable by taking an advantage of quantum-interference-switchable optical response of EIT. The transmittance of the 4-layer and 6-layer periodic (D|E) cells when the Rabi frequency of the control field varies is plotted in Fig. 4, where Ω_c changes from $2\Gamma_3$ to $20\Gamma_3$.

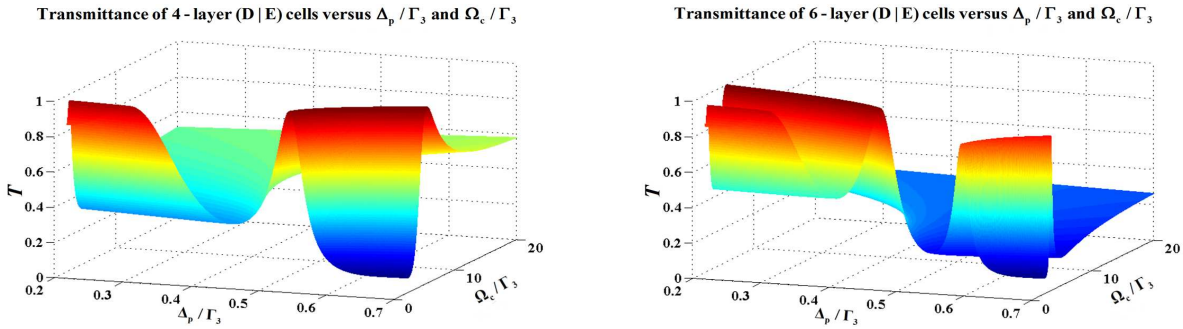
Transmittance of 4-layer (D|E) cells versus Δ_p/Γ_3 and Ω_c/Γ_3
Transmittance of 6-layer (D|E) cells versus Δ_p/Γ_3 and Ω_c/Γ_3
T
Δ_p/Γ_3
Ω_c/Γ_3

Fig. 4. The dispersive and tunable optical response in the transmittance of the 4-layer and 6-layer periodic (D|E) cells with $\Omega_c = 2\Gamma_3 \sim 20\Gamma_3$ and $\Delta_p = 0.2\Gamma_3 \sim 0.7\Gamma_3$.

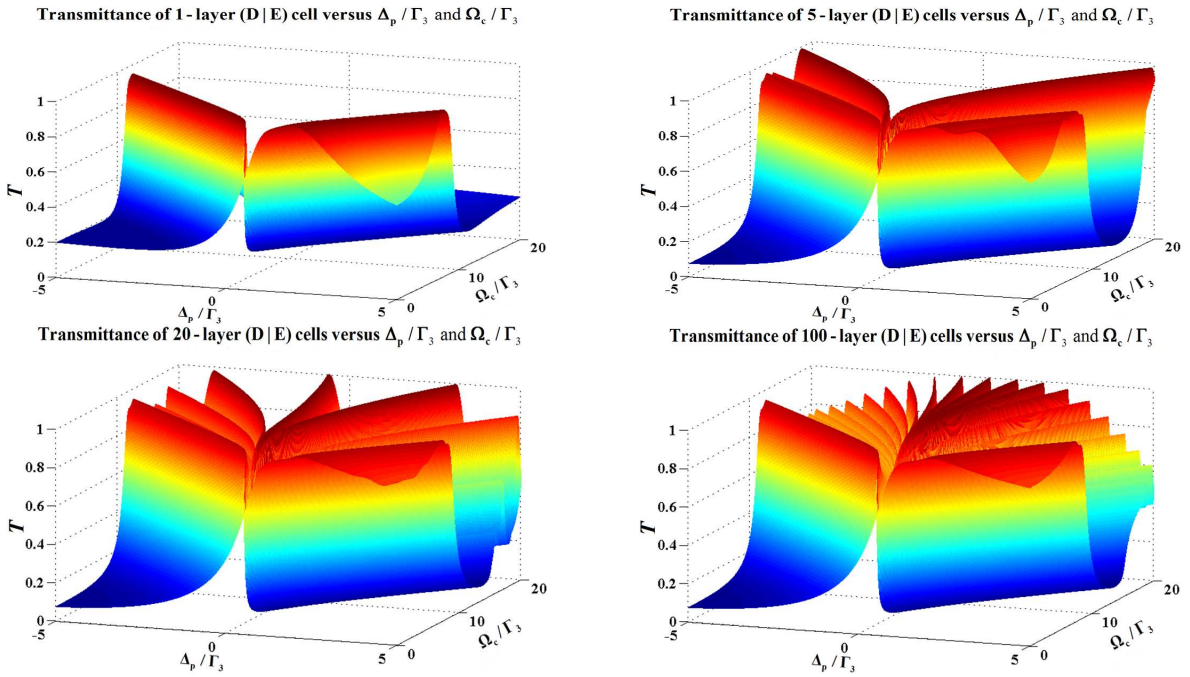
Transmittance of 1-layer (D|E) cell versus Δ_p/Γ_3 and Ω_c/Γ_3
Transmittance of 5-layer (D|E) cells versus Δ_p/Γ_3 and Ω_c/Γ_3
Transmittance of 20-layer (D|E) cells versus Δ_p/Γ_3 and Ω_c/Γ_3
Transmittance of 100-layer (D|E) cells versus Δ_p/Γ_3 and Ω_c/Γ_3
T
Δ_p/Γ_3
Ω_c/Γ_3

Fig. 5. General behavior of tunable optical response of the N-layer periodic (D|E) cells with $N = 1,\ 5,\ 20,\ 100$.

The other functional and logic gates, such as two-input AND, NOT, NOR, EXOR and EXNOR gates, can also be designed based on this sensitive switching control effect due to two-photon resonance exhibited in such an EIT-based periodic layered structure. For this purpose, we need to utilize the tunable optical behavior of the EIT-based periodic medium in a wide range of probe frequency detuning, as indicated in Fig. 5, where we have presented the general behavior of tunable optical response of the N -layer periodic (D|E) cells ($N = 1,\ 5,\ 20,\ 100$).

A generalization to a double-control quantum interference

The destructive and constructive quantum interferences would be exhibited in a four-level double-control atomic system, where the probe transition (driven by the probe field) can be manipulated by the quantum interferences between two control transitions (driven by the two control fields) of the four-level system [5,9]. The atomic vapor is opaque (or transparent) to the probe field if the destructive (or constructive) quantum interference between the control transitions emerges. Consider a four-level atomic system with three lower levels $|1\rangle, |2\rangle, |2'\rangle$ and one upper level $|3\rangle$ (see Fig. 7). Such an atomic system interacts with three optical fields, i.e., the two control laser beams and one probe laser beam, which couple the level pairs $|2\rangle$-$|3\rangle$, $|2'\rangle$-$|3\rangle$ and $|1\rangle$-$|3\rangle$, respectively. The three frequency detunings Δ_c, $\Delta_{c'}$ and Δ_p are defined as follows: $\Delta_c = \omega_{32} - \omega_c$, $\Delta_{c'} = \omega_{32'} - \omega_{c'}$, and $\Delta_p = \omega_{31} - \omega_p$. According to the Schrödinger equation, one can obtain the equation of motion of the density matrix elements of the present atomic system

$$\begin{aligned}
\dot{\rho}_{21} &= -\left[\frac{\gamma_2}{2} + \mathrm{i}\left(\Delta_p - \Delta_c\right)\right]\rho_{21} + \frac{\mathrm{i}}{2}\Omega_c^{*}\rho_{31}, \\
\dot{\rho}_{21} &= -\left[\frac{\gamma_2'}{2} + \mathrm{i}\left(\Delta_p - \Delta_{c'}\right)\right]\rho_{2'1} + \frac{\mathrm{i}}{2}\Omega_{c'}^{*}\rho_{31}, \\
\dot{\rho}_{31} &= -\left(\frac{\Gamma_3}{2} + \mathrm{i}\Delta_p\right)\rho_{31} + \frac{\mathrm{i}}{2}\left(\Omega_p\rho_{11} + \Omega_c\rho_{21} + \Omega_{c'}\rho_{2'1}\right).
\end{aligned} \tag{2}$$

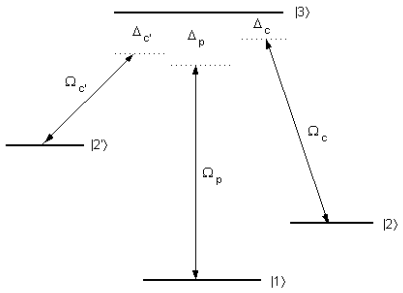

Fig. 6. The schematic diagram of a double-control four-level system. The two control laser beams, Ω_c and $\Omega_{c'}$, drive the $|2\rangle$-$|3\rangle$ and $|2'\rangle$-$|3\rangle$ transitions, respectively. The probe transition $|1\rangle$-$|3\rangle$ can be controllably manipulated via the destructive and constructive quantum interferences between the $|2\rangle$-$|3\rangle$ and $|2'\rangle$-$|3\rangle$ transitions. If levels $|1\rangle$, $|2\rangle$, and $|2'\rangle$ form a three-level dark state, the atomic vapor is transparent to the probe field, while it is opaque to the probe field when levels $|2\rangle$ and $|2'\rangle$ form a two-level dark state.

We assume that the intensity of the probe beam is sufficiently weak and therefore nearly all the atoms remain in the ground state, i.e., the atomic population in level $|1\rangle$ is unity. The density matrix elements of levels $|2\rangle$, $|2'\rangle$ and $|3\rangle$ are given by

$$\rho_{21}=-\frac{1}{4D}\Omega_{\mathrm{p}}\Omega_{\mathrm{c}}^{*}\left[\frac{\gamma_2^{'}}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}'}\right)\right],$$

$$\rho_{2'1}=-\frac{1}{4D}\Omega_{\mathrm{p}}\Omega_{\mathrm{c}'}^{*}\left[\frac{\gamma_2}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}}\right)\right], \tag{3}$$

$$\rho_{31}=\frac{\mathrm{i}}{2D}\Omega_{\mathrm{p}}\left[\frac{\gamma_2}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}}\right)\right]\left[\frac{\gamma_2^{'}}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}'}\right)\right],$$

$$\begin{aligned}D=&\left(\frac{\Gamma_3}{2}+\mathrm{i}\Delta_{\mathrm{p}}\right)\left[\frac{\gamma_2}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}}\right)\right]\left[\frac{\gamma_2^{'}}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}'}\right)\right]\\&+\frac{1}{4}\Omega_{\mathrm{c}}^{*}\Omega_{\mathrm{c}'}\left[\frac{\gamma_2}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}}\right)\right]+\frac{1}{4}\Omega_{\mathrm{c}}^{*}\Omega_{\mathrm{c}}\left[\frac{\gamma_2^{'}}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}'}\right)\right].\end{aligned} \tag{4}$$

The atomic electric polarizability of the double-control four-level atomic vapor is of the form

$$\beta\left(\Delta_{\mathrm{p}},\Omega_{\mathrm{c}},\Omega_{\mathrm{c}'}\right)=\frac{\left|\wp_{13}\right|^2}{\varepsilon_0\hbar}\frac{\mathrm{i}}{D}\left[\frac{\gamma_2}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}}\right)\right]\left[\frac{\gamma_2^{'}}{2}+\mathrm{i}\left(\Delta_{\mathrm{p}}-\Delta_{\mathrm{c}'}\right)\right]. \tag{5}$$

The relative electric permittivity with local field correction is

$$\varepsilon_{\mathrm{r}}\left(\Delta_{\mathrm{p}},\Omega_{\mathrm{c}},\Omega_{\mathrm{c}'}\right)=1+\frac{N\beta\left(\Delta_{\mathrm{p}},\Omega_{\mathrm{c}},\Omega_{\mathrm{c}'}\right)}{1-\dfrac{N\beta\left(\Delta_{\mathrm{p}},\Omega_{\mathrm{c}},\Omega_{\mathrm{c}'}\right)}{3}}. \tag{6}$$

The most remarkable feature of the present scheme is that the optical properties (absorption, transparency and dispersion) of the atomic system can be controllably manipulated by the double-control multi-pathway interferences (multiple routes to excitation). The four-level system will exhibit two-level resonant absorption when the two control levels (driven by the two control fields) form a dark state (and hence the destructive quantum interference occurs between the two control transitions). However, the present four-level system will exhibit electromagnetically induced transparency to the probe field when the three lower levels (including the probe level and two control levels) form a three-level dark state. Similar to the preceding three-level EIT photonic crystals, an alternative scenario to manipulate the probe transitions (and hence the optical properties) via the combination of double-control (destructive and constructive) quantum interferences and photonic crystal can be suggested. The optically sensitive responses due to the double-control quantum interferences can also be utilized to realize the logic-gate devices. The further work will be published elsewhere.

Conclusions

The EIT medium and the photonic crystal, which are the two of the most intriguing artificial electromagnetic materials in optics and electromagnetic material regimes, have captured extensive attention of many researchers in various fields [11,12]. We have proposed a periodic layered structure with unit cells composed of dielectric (e.g., GaAs) and EIT atomic vapor, and demonstrated the frequency-sensitive optical response (due to two-photon resonance of EIT) in such an EIT-based photonic crystal. As the quantum interference induced by external control field makes an essential contribution to the optical response (two-photon resonance), the reflectance and transmittance of such a periodic layered medium is tunable as the intensity of the external control field varies, and would have potential applications in designs of new photonic and quantum optical devices. The present scheme can be generalized to a four-level EIT system, where two control fields and one probe field drive the atomic level transitions. Obviously, the reflectance and transmittance in such an EIT-based photonic crystal would be more sensitive to the probe frequency than in a three-level EIT-based photonic crystal presented in this paper.

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